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UTILITY PATENT APPLICATION TRANSMITTAL

Only for new nonprovisional applications under 37 CFR 1.53(b))

Attorney Docket No.	E0794
First Inventor	Subramanian, et al.
Title	SYSTEM FIR RAPIDLY AND UNIFORM
Express Mail Label No.	EF185629327US

APPLICATION ELEMENTS

See MPEP chapter 600 concerning utility patent application contents.

ADDRESS TO: Assistant Commissioner for Patents, Box Patent Application, Washington, DC 20231

1. [✓] Fee Transmittal Form (e.g., PTO/SB/17) (Submit an original and a duplicate for fee processing)
2. [ ] Applicant claims small entity status. See 37 CFR 1.27.
3. [✓] Specification [Total Pages 18] (preferred arrangement set forth below)
   - Descriptive title of the invention
   - Cross Reference to Related Applications
   - Statement Regarding Fed sponsored R & D
   - Reference to sequence listing, a table, or a computer program listing appendix
   - Background of the Invention
   - Brief Summary of the Invention
   - Brief Description of the Drawings (if filed)
   - Detailed Description
   - Claim(s)
   - Abstract of the Disclosure
4. [✓] Drawing(s) (35 U.S.C. 113) [Total Sheets 5]
5. Oath or Declaration [Total Pages 3]
   - a. [✓] Newly executed (original or copy)
   - b. [ ] Copy from a prior application (37 CFR 1.63 (d)) (for continuation/divisional with Box 17 completed)
     - i [ ] DELETION OF INVENTOR(S) Signed statement attached deleting inventor(s) named in the prior application, see 37 CFR 1 63(d)(2) and 1 33(b).
6. [ ] Application Data Sheet. See 37 CFR 1.76
7. [ ] CD-ROM or CD-R in duplicate, large table or Computer Program (Appendix)
8. Nucleotide and/or Amino Acid Sequence Submission (if applicable, all necessary)
   - a. [ ] Computer Readable Form (CRF)
   - b. Specification Sequence Listing on:
     - i. [ ] CD-ROM or CD-R (2 copies); or
     - ii. [ ] paper
   - c. [ ] Statements verifying identity of above copies

ACCOMPANYING APPLICATION PARTS

9. [✓] Assignment Papers (cover sheet & document(s))
10. [ ] 37 CFR 3.73(b) Statement (when there is an assignee) [ ] Power of Attorney
11. [ ] English Translation Document (if applicable)
12. [ ] Information Disclosure Statement (IDS)/PTO-1449 [ ] Copies of IDS Citations
13. [ ] Preliminary Amendment
14. [✓] Return Receipt Postcard (MPEP 503) (Should be specifically itemized)
15. [ ] Certified Copy of Priority Document(s) (if foreign priority is claimed)
16. [✓] Other: Express Mail Certificate

17. If a CONTINUING APPLICATION, check appropriate box, and supply the requisite information below and in a preliminary amendment, or in an Application Data Sheet under 37 CFR 1.76:

[ ] Continuation [ ] Divisional [ ] Continuation-in-part (CIP) of prior application No ________/________

Prior application information Examiner ____________ Group / Art Unit ____________

For CONTINUATION OR DIVISIONAL APPS only: The entire disclosure of the prior application, from which an oath or declaration is supplied under Box 5b, is considered a part of the disclosure of the accompanying continuation or divisional application and is hereby incorporated by reference. The incorporation can only be relied upon when a portion has been inadvertently omitted from the submitted application parts.

18. CORRESPONDENCE ADDRESS

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Signature		Date	November 6, 2000

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TOTAL AMOUNT OF PAYMENT ($) 928.00

Complete if Known	
Application Number	
Filing Date	Herewith
First Named Inventor	Subramanian, et al.
Examiner Name	
Group Art Unit	
Attorney Docket No.	E0794

METHOD OF PAYMENT

1. [x] The Commissioner is hereby authorized to charge indicated fees and credit any overpayments to

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Deposit Account Name: Amin, Eschweiler & Turocy, LLP

[x] Charge Any Additional Fee Required Under 37 CFR 1 16 and 1.17

[ ] Applicant claims small entity status See 37 CFR 1 27

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FEE CALCULATION

1. BASIC FILING FEE

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description	Fee Paid
101	710	201	355	Utility filing fee	710
106	320	206	160	Design filing fee	
107	490	207	245	Plant filing fee	
108	710	208	355	Reissue filing fee	
114	150	214	75	Provisional filing fee	

SUBTOTAL (1) ($) 710.00

2. EXTRA CLAIM FEES

			Extra Claims		Fee from below		Fee Paid
Total Claims	21	-20** =	1	X	18	=	18
Independent Claims	5	- 3** =	2	X	80	=	160
Multiple Dependent					0	=	0

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description
103	18	203	9	Claims in excess of 20
102	80	202	40	Independent claims in excess of 3
104	270	204	135	Multiple dependent claim, if not paid
109	80	209	40	** Reissue independent claims over original patent
110	18	210	9	** Reissue claims in excess of 20 and over original patent

SUBTOTAL (2) ($) 178.00

***or number previously paid, if greater, For Reissues, see above*

FEE CALCULATION (continued)

3. ADDITIONAL FEES

Large Entity Fee Code	Large Entity Fee ($)	Small Entity Fee Code	Small Entity Fee ($)	Fee Description	Fee Paid
105	130	205	65	Surcharge - late filing fee or oath	
127	50	227	25	Surcharge - late provisional filing fee or cover sheet	
139	130	139	130	Non-English specification	
147	2,520	147	2,520	For filing a request for *ex parte* reexamination	
112	920*	112	920*	Requesting publication of SIR prior to Examiner action	
113	1,840*	113	1,840*	Requesting publication of SIR after Examiner action	
115	110	215	55	Extension for reply within first month	
116	390	216	195	Extension for reply within second month	
117	890	217	445	Extension for reply within third month	
118	1,390	218	695	Extension for reply within fourth month	
128	1,890	228	945	Extension for reply within fifth month	
119	310	219	155	Notice of Appeal	
120	310	220	155	Filing a brief in support of an appeal	
121	270	221	135	Request for oral hearing	
138	1,510	138	1,510	Petition to institute a public use proceeding	
140	110	240	55	Petition to revive - unavoidable	
141	1,240	241	620	Petition to revive - unintentional	
142	1,240	242	620	Utility issue fee (or reissue)	
143	440	243	220	Design issue fee	
144	600	244	300	Plant issue fee	
122	130	122	130	Petitions to the Commissioner	
123	50	123	50	Petitions related to provisional applications	
126	240	126	240	Submission of Information Disclosure Stmt	
581	40	581	40	Recording each patent assignment per property (times number of properties)	40.00
146	710	246	355	Filing a submission after final rejection (37 CFR § 1 129(a))	
149	710	249	355	For each additional invention to be examined (37 CFR § 1 129(b))	
179	710	279	355	Request for Continued Examination (RCE)	
169	900	169	900	Request for expedited examination of a design application	

Other fee (specify) ______________________________

* Reduced by Basic Filing Fee Paid

SUBTOTAL (3) ($) 40.00

SUBMITTED BY				Complete *(if applicable)*	
Name (Print/Type)	Himanshu S. Amin	*Registration No (Attorney/Agent)*	40,984	*Telephone*	216-696-8730
Signature	[signature]			*Date*	November 6, 2000

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Atty. Docket No. E0794

SYSTEM FOR RAPIDLY AND UNIFORMLY COOLING RESIST

by

Ramkumar Subramanian, Bharath Rangarajan
and Michael K. Templeton

CERTIFICATION UNDER 37 CFR 1.10

I hereby certify that the attached patent application (along with any other paper referred to as being attached or enclosed) is being deposited with the United States Postal Service on this date November 6, 2000, in an envelope as "Express Mail Post Office to Addressee" Mailing Label Number EF185629327US addressed to the: Box Patent Application, Assistant Commissioner for Patents, Washington, D.C. 20231.

Himanshu S. Amin
(Typed or Printed Name of Person Mailing Paper)

(Signature of Person Mailing Paper)

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TITLE: **SYSTEM FOR RAPIDLY AND UNIFORMLY COOLING RESIST**

Technical Field

The present invention relates to semiconductor processing and in particular to a system for uniformly and rapidly cooling a resist.

Background of the Invention

In the semiconductor industry, there is a continuing trend toward higher device densities. To achieve these high densities there has been, and continues to be, efforts toward scaling down the device dimensions (*e.g.*, at submicron levels) on semiconductor wafers. In order to accomplish such high device packing density, smaller and smaller features sizes are required. This may include the width and spacing of interconnecting lines, spacing and diameter of contact holes, and the surface geometry such as corners and edges of various features.

The requirement of small features with close spacing between adjacent features requires high resolution lithographic processes. In general, lithography refers to processes for pattern transfer between various media. It is a technique used for integrated circuit fabrication in which a silicon slice, the wafer, is coated uniformly with a radiation-sensitive film, the resist, and the film exposed with a radiation source (such as optical light, x-rays, or an electron beam) that illuminates selected areas of the surface through an intervening master template, the mask, forming a particular pattern. The lithographic coating is generally a radiation-sensitive coating suitable for receiving a projected image of the subject pattern. Once the image is projected, it is indelibly formed in the coating. The projected image may be either a negative or a positive image of the subject pattern. Exposure of the coating through a photomask causes the image area to become either more or less soluble (depending on the coating) in a particular solvent developer. A positive-tone resist is one that becomes more soluble in the developer after exposure to actinic radiation. A negative-tone resist becomes less soluble in the developer after exposure. The more soluble areas are removed in the developing process to leave the pattern image in the coating.

A resist coating is typically prepared by dripping or spraying a resist solution

onto a spinning substrate. This forms a relatively uniform coating of the resist solution, which is then "soft-baked." Soft-baking drives off solvent, improves adhesion of the resist to the substrate, and anneals stresses caused by shear forces encountered in the spinning process. Typically, the solvent level is reduced from the 20% to 30% range to about the 4% to 7% range.

The time and temperature of the soft-bake determines a number of parameters that affect subsequent processing steps. The degree of soft-baking affects the residual solvent content of the resist, which in turn affects the rate of attack of the resist by the developer. Under-baked resists may show inadequate differentiation between the dissolution rates of exposed and un-exposed regions. On the other hand, over-baking reduces photosensitivity of the resist, which also reduces the ability to create sharp contrast between exposed and unexposed regions. Consequently, the soft-bake must be carefully optimized and controlled.

Particularly where extremely fine patterns are sought, the pre-bake process must not only be controlled from substrate to substrate, but also across each individual substrate. Both the overall temperature history and variations in the temperature across the photoresist must be controlled. Variation in the temperature history across the substrate during pre-bake can lead, after exposure of the resist, to unintended lengthwise variations in the width of features such as lines and gaps. Chemically amplified photoresists are particularly susceptible to such variations. The feature sizes of chemically amplified photoresists can be drastically affected by only a few degrees difference in temperature. Line size deviations often occur unless temperature is maintained within 0.5°C tolerance across the substrate. Temperature control within ± 0.2°C may be required.

Much attention has been given to systems for uniformly heating photoresist coated substrates. While convection ovens have been used, they have limitations. The temperature uniformity of convection ovens is not particularly good and particles may enter the ovens and become embedded in the heated resist. Infrared ovens have been widely utilized. These ovens have much shorter heating times than convection ovens (3-4 minutes versus approximately 30 minutes). Hot-plates also permit rapid heating.

Less attention has been given to cooling systems, although several have been

suggested. Natural convection cooling under ambient conditions has been used, but this is relatively slow and results in substantial non-uniformities. Cold-plates are somewhat better. These can be cooled by cooling fluids or Peltier elements. However, substrate temperature gradients form when using cold plates, since heat must travel from the substrates and the surroundings to the cold plates. It has been proposed to submerge the substrates in a liquid such as water. Cooling in this case may be too rapid and cause mechanical damage to the substrate. Submerging also has the disadvantage of requiring a drying step. Use of a cooling gas has been suggested, but a cooling gas does not appear to have been successfully used to achieve uniform cooling.

Therefore, there remains an unsatisfied need for a system and method of rapidly and uniformly cooling resist coated substrates.

Summary of the Invention

According to the invention, resist coated wafers are rapidly and uniformly cooled by a fluid that has been cooled through the Joule-Thompson effect. Fluid from a high pressure reservoir is vented into a chamber that contains the substrates. By varying the pressure difference between the reservoir and the chamber, the temperature of the cooling fluid entering the chamber can be controlled. By also controlling the flow rate through the chamber, the average temperature difference between the fluid in the chamber and the substrates may be limited, whereby more uniform cooling is obtained. While the chamber pressure is lower than that in the high pressure reservoir, the chamber pressure may still be substantially greater than atmospheric. An elevated chamber pressure raises the specific heat and residence time of the fluid in the chamber, which also promotes uniform cooling.

In one aspect, the invention provides a system including a chamber adapted to receive one or more coated semiconductor substrates, a coupling for placing the chamber in fluid communication with a fluid reservoir, an inlet valve controlling the flow of fluid between the fluid reservoir and the chamber, and a controller that controls the inlet valve.

In another aspect, the invention provides a system for cooling coated semiconductor substrates including means for cooling a fluid by at least about 10 °C

through the Joule-Thompson effect and means for contacting the cooled fluid with the substrates.

In a further aspect, the invention provides a method of cooling coated semiconductor substrates including the steps of cooling a fluid by at least about 10 °C through the Joule-Thompson effect and contacting the substrates with the cooled fluid.

In a further aspect, the invention provides a method of cooling coated semiconductor substrates including the steps of heating a fluid to a temperature above ambient, subsequently flowing the fluid into a chamber containing the substrates, and cooling the substrates by contacting them with the fluid that has been heated.

In a further aspect, the invention provides a system for cooling coated semiconductor substrates including a first sub-system for cooling a fluid using the Joule-Thompson effect and a second sub-system for contacting the coated semiconductor substrates with the cooled fluid.

The invention extends to features hereinafter fully described and particularly pointed out in the claims. The following description and the annexed drawings set forth in detail certain illustrative examples of the invention. These examples are indicative, however, of but a few of the various ways in which the principles of the invention may be employed. Other objects, advantages and novel features of the invention will become apparent from the following detailed description of the invention when considered in conjunction with the drawings.

Brief Description of the Drawings

Fig. 1a is a general schematic of a system according to the present invention for cooling coated semiconductor substrates.

Fig. 1b is another schematic of a system according to the present invention for cooling a coated semiconductor substrate.

Fig. 2 is a flow diagram of a control strategy for use with a process of the present invention.

Fig. 3 is a flow diagram of another control strategy for use with a process of the present invention.

Fig. 4 is a flow diagram of still another a control strategy for use with a

process of the present invention.

Detailed Description of the Invention

The present invention will now be described with reference to the drawings, wherein like reference numerals are used to refer to like elements throughout.

Fig. 1a is a general schematic of a cooling system 10 in accordance with the present invention. Cooling system 10 includes a first sub-system 20 in which a fluid is cooled through the Joule-Thompson effect and a second sub-system 30 in which the cooled fluid is contacted with one or more coated semiconductor substrates 40.

Fig. 1b is a schematic of a cooling system 100 in accordance with the present invention. System 100 includes high pressure reservoir 110, inlet valve 140, chamber 180, outlet valve 220, and controller 150. In accordance with a method of the present invention, one or more coated substrates 190 are cooled by venting fluid from high pressure reservoir 110 into chamber 180, which contains substrates 190. Fluid is vented into chamber 180 through inlet valve 140 and released through outlet valve 220 to exhaust 240, whereby a continuous flow of cooling fluid and constant pressure may be maintained within chamber 180. Controller 150 monitors the cooling process through substrate temperature sensor 250 and controls the process by manipulating inlet valve 140 and outlet valve 220. Additional information may be provided to controller 150 by inlet valve 140, outlet valve 220, flow meter 230, reservoir fluid temperature sensor 260, chamber inlet temperature sensor 270, and chamber exhaust temperature sensor 280. This information may be used by controller 150 to maximize the cooling rate while limiting temperature variations within and among substrates 190.

The substrates are typically semi-conducting materials, such as silicon. In addition to a semiconducting material, the substrates may include various elements and/or layers; including metal layers, barrier layers, dielectric layers, device structures, active elements and passive elements including silicon gates, word lines, source regions, drain regions, bit lines, bases emitters, collectors, conductive lines, conductive plugs, etc. Sudden temperature changes may result in delamination or detachment of the substrate coating, substrate layers, or substrate devices.

The substrate coating may be of any type. It may be liquid or solid. Generally,

the coating will have properties that are sensitive to temperature. The invention is particularly useful when the coating is a resist. The resist may be organic or inorganic. It may be a photoresist responsive to visible light, ultraviolet light, or x-rays, or it may be an electron beam resist or an ion beam resist. The resist may be positive or negative tone. The resist may be chemically amplified, whereby its sensitivity to actinic radiation is enhanced.

Substrates 190 are contained in chamber 180. This chamber may be the same chamber that was used to heat the coated substrates. On the other hand, it may be a separate chamber. Using the same chamber to heat and cool the substrates has the advantages of not having to move the substrate and avoiding exposure of the substrates to uncontrolled temperature changes during the transportation process. On the other hand, using one chamber for heating and cooling increases the cooling requirement. For example system 100 includes heating plate 210. Heating plate 210 increases the cooling requirement. Substrates may be moved from a heating chamber to a cooling chamber quickly and automatically, by a robotic arm for example.

Substrates 190 are supported on pins 200 over hot plate 210. The cooling process is facilitated by ensuring hot plate 210, or whatever structure supports the substrates, has a low thermal inertia. Pins 200 reduces the risk of contamination of substrates 190 by the structure on which the substrates are supported.

Substrates 190 are cooled by venting fluid from high pressure reservoir 110 into chamber 180 through inlet valve 140. In one aspect of the invention, the pressure drop across valve 140 is at least about 1 bar. In another aspect, the pressure drop is at least about 10 bar. In a further aspect, the pressure drop is at least about 100 bar. Reservoir 110 is usually a high pressure gas cylinder, although it could be the outlet of a pump. The fluid generally cools as it is vented into chamber 180. In one aspect of the invention, it cools by at least about 10 °C. In another aspect, it cools by at least about 25 °C. In a further aspect, it cools by at least about 50 °C.

Reservoir 100 is in fluid communication with chamber 180 through coupling 120. Coupling 120, or another part of the system, may include a means of excluding particles from the fluid stream. The means may be a filter in coupling 120 to remove particles from the fluid, or may involve providing a fluid source that is relatively free of particles. Particles in the cooling fluid may contaminate the substrates, if not

controlled.

The fluid can be any fluid that exhibits the Joule-Thomson effect in the temperature range of interest and is chemically inert with respect to coated substrates 190. The Joule-Thomson effect is the cooling of a fluid upon adiabatic expansion. When a fluid expands freely from a high pressure reservoir into a lower pressure chamber, as in expansion through a valve, the process is generally, to a good approximation, adiabatic. The change of temperature can be determined from the pressure change and the formula:

$$dT / dP = (T / C_P)(\partial V / \partial T)_P - TV / C_P$$

If the expression on the right hand side is positive for a particular gas at a particular temperature and pressure, the gas will exhibit the Joule-Thompon effect under those conditions. Nitrogen will exhibit the Joule-Thomson effect between the temperatures of -156 and 277 °C. Nitrogen can therefore be used in the invention. Carbon dioxide, and in some cases air, can also be used.

While the fluid may condense as it cools, this may or may not be an advantage depending on the physical configuration of the system. Cooling through condensation is very rapid and provides a comparatively constant temperature in the cooling medium. However, cooling by condensation may be too rapid and result in excessive temperature gradients within the substrates. Therefore, it is advantageous to use a fluid that has a relatively high thermal inertia but does not liquify or form a two phase system upon venting into the chamber. Supercritical carbon dioxide can be used to achieve rapid cooling without phase changes.

Fluid from reservoir 110 vents into chamber 180 through inlet valve 140. Inlet valve 140 may be any type of valve that allows a reasonably controlled rate of flow over a range of settings. For example, it may be a ball valve, a globe valve, or a needle valve. A needle valve can be used to achieve precise flow control.

Venting fluid into chamber 180 and exhausting it through valve 200 causes convention within chamber 180, but it may be beneficial to increase convention within chamber 180, using fan 160 for example. Increasing convention within chamber 180 increases heat transfer between the cooling fluid and substrates 190. Thereby, the rate of cooling is increased. If convection within chamber 180 is increased without increasing the rate of flow though chamber 180, uniformity of

temperature within the cooling fluid increases, making the cooling process more uniform as well.

Fluid is released from chamber 180 through exhaust valve 220. Like inlet valve 140, exhaust valve 220 may be any type of valve that allows a reasonably controlled rate of flow over a range of settings. For example, it may be a ball valve, a globe valve, or a needle valve. Exhaust valve 220, and inlet valve 140, may provide controller 150 with an indications of their position, *e.g.*, whether and to what extent they are open.

Inlet valve 140 and outlet valve 220 can be adjusted independently to separately control the flow rate of cooling fluid through chamber 180 and the pressure drop across inlet valve 140. The pressure drop 140 affects the temperature of the cooling fluid as it enters chamber 180. Therefore, inlet valve 140 and outlet valve 220 can be used to independently control two parameters, such as the temperature of the cooling fluid as it enters chamber 180 and the flow rate of cooling fluid through chamber 180.

Temperature sensors 250, 260, 270, and 280 table suitable type for the temperatures and media (fluid or solid) that are being measured. For example, they may be thermocouples, thermistors, resistance temperature detectors, or radiation thermometers. Preferably, temperature sensor 250 senses the temperature of substrates 290 without touching or contaminating them. A sensor based on reflected radiation may be used. For example, temperature sensor 250 may be an interferometer detecting thermal expansion or a spectrophotometer detecting changes in fluorescence or color. Temperature sensor 250 samples the substrate temperature at one point. However, multiple sensors giving an average temperature can also be used. Alternatively, sensor 250 may measure the temperature of an object that has a temperature approximating that of the substrate. For example, temperature sensor 250 may sense the temperature of hot plate 210.

Pressure sensors 130 and 170 and flow meter 230 may be of conventional types. Flow meter 230 may be, for example, a thermal dispersion mass flow meter, a differential pressure flow meter, a positive displacement flow meter, or a Coriolis mass flow meter.

In a method of the invention, fluid from reservoir 110 is vented into chamber

180 at a controlled rate and temperature. The rate and temperature may be set by controller 150 thorough manipulation of inlet valve 140 and outlet valve 220.

The rate at which the substrates are cooled, q_S, may be represented by the following equation:

$$q_S = H_S\,(T_S - T_C)$$

where H_S is an overall heat transfer coefficient, T_S is the substrate temperature, and T_C is the average temperature of the fluid in the chamber. The heat taken up by the substrates must equal the heat released by the flowing fluid. Assuming that the fluid leaving the chamber is at the average temperature for fluid in the chamber:

$$q_S = F\,C_V\,(T_C - T_I)$$

where F is the volumetric flow rate of cooling fluid, C_V is the fluid's heat capacity on a unit volume basis, and T_I is the temperature of the fluid entering the chamber. Solving for the average chamber temperature:

$$T_C = (H_S\,T_S - F\,C_V\,T_I)\,/\,(H_S + F\,C_V)$$

When the heat transfer coefficient is very high in comparison with the flow rate, the average temperature of the fluid in the chamber approaches the substrate temperature. When the flow rate is high compared to the heat transfer coefficient, the average temperature of the fluid in the chamber approaches the temperature of the fluid entering the chamber.

Uniform cooling of the substrate may be facilitated by keeping the average temperature of fluid in the chamber comparatively close to the substrate temperature. This slows the cooling rate, allowing time for heat to disperse evenly. Reducing the temperature difference between the fluid in the chamber and the substrates may also reduce the size of temperature differences within the cooling fluid near the substrates. To realize this latter benefit, it is preferable that cooling fluid entering the chamber does not contact the substrates immediately. Rather, it is advantageous if the entering fluid flow is directed against a wall or a baffle, whereby the cooling fluid entering the chamber substantially mixes with the fluid already in the chamber before contacting the substrates.

Uniform cooling may also be facilitated by having the degree of re-circulation or mixing within the chamber high relative to the flow rate through the chamber. The ratio of re-circulation to that of flow through may be increased by reducing the flow

rate, particularly when a fan or other device forces convection within the chamber.

Rapid cooling may be facilitated by increasing the temperature difference between the chamber fluid and the substrates. The temperature difference may be increased by increasing the flow rate of cooling fluid and/or reducing the temperature of the fluid entering the chamber.

A balance between cooling rate and cooling uniformity may need to be struck. The location of that balance and the control strategy used to obtain it depends on the demands of the particular application and the physical configuration of the chamber and the substrates. The control strategy may be implemented by controller 150. Controller 150 is a logic circuit, such as a programmable logic circuit. Typically, controller 150 includes a microprocessor and a memory containing suitable software instructions.

A control strategy 300, which may be effective in obtaining uniform cooling, is illustrated in Fig. 2. Strategy 300 seeks a constant cooling fluid temperature at the inlet and a fixed temperature difference between the substrate and the average cooling fluid in chamber 190. An advantage of this strategy is that is conserves the use of cooling fluid from high pressure reservoir 110. In step 310, The inlet fluid temperature is measured by sensor 270. In step 320, controller 150 compares the inlet fluid temperature to the target value. If the inlet fluid temperature is greater than the target value, inlet valve 140 is incrementally closed in step 340. Incrementally closing inlet valve 140 tends to decrease the chamber pressure, increase the pressure drop across inlet valve 140, and decrease the inlet gas temperature. If the inlet fluid temperature is less than the target value, inlet valve 140 is incrementally opened in step 330. Incrementally opening inlet valve 140 tends to increase the chamber pressure, decrease the pressure drop across inlet valve 140, and increase the inlet gas temperature.

In step 350, the substrate temperature is measured by sensor 250 and the average chamber fluid temperature is measured (approximately) by sensor 280. Controller 150 compares the difference between these two temperatures to a target difference in step 360. If the temperature difference is greater than the target, outlet valve 220 is incrementally closed in step 380. Incrementally closing outlet valve 220 decreases the flow rate through the chamber, which tends to decrease the temperature

difference between the fluid in the chamber and the substrate. If the temperature difference is less than the target, outlet valve 220 is incrementally opened in step 370. Incrementally opening outlet valve 220 increases the flow rate through the chamber, which tends to increase the temperature difference between the fluid in the chamber and the substrate. The steps, beginning again with step 310, are repeated.

Strategy 300 may be improved by simultaneously adjusting both the inlet and outlet valves taking into account the results of both comparisons. While strategy 300 uses inlet valve 140 to adjust the inlet fluid temperature and outlet valve 220 to adjust the temperature difference, adjustments to inlet valve 140 affect the temperature difference and adjustments to outlet valve 220 affect the inlet fluid temperature. Using a mathematical model, these cross-correlations could be taken into account and both valves adjusted simultaneously. These and other possible improvements in this and other control strategies discussed herein will be readily apparent to one of ordinary skill in the art.

Another control strategy 400 that may be effective in obtaining a uniform rate of cooling is illustrated in Fig. 3. Strategy 400 uses a constant flow rate throughout the cooling process and also maintains a fixed temperature difference between the substrate and the cooling fluid in chamber 190. Keeping the flow rate low in comparison to the re-circulation or mixing rate within chamber 190 is particularly effective in obtaining uniform cooling rates. In step 410, the flow rate is measured by flow meter 230. In step 420, controller 150 compares the flow rate to the target value. If the flow rate is greater than the target value, outlet valve 220 is incrementally closed in step 440. If the flow rate is less than the target value, outlet valve 220 is incrementally opened in step 430.

In step 450, the substrate temperature is measured by sensor 250 and the average chamber fluid temperature is measured (approximately) by sensor 280. Controller 150 compares the difference between these two temperatures to a target difference in step 460. If the temperature difference is greater than the target, inlet valve 140 is incrementally opened in step 480. Incrementally opening inlet valve 140 while keeping the flow rate constant, through adjustments to outlet valve 220, increases the pressure in the chamber, decreases the pressure drop across inlet valve 140, and increases the temperature of the cooling fluid. If the temperature difference

is less than the target, inlet valve 140 is incrementally closed in step 470. Incrementally closing inlet valve 140 while keeping the flow rate constant, through adjustments to outlet valve 220, decreases the pressure in the chamber, increases the pressure drop across inlet valve 140, and decreases the temperature of the cooling fluid.

Control strategy 400 demonstrates that it may be desirable to heat the fluid in reservoir 110 while it is in the reservoir or as it flow from reservoir 110 to chamber 190. Ordinarily, adjusting the pressure drop across inlet valve 140 permits the inlet fluid temperature to be adjusted only in the range at or below the reservoir temperature. In a constant flow rate process, heating the cooling fluid may be desirable to reduce the temperature difference between the cooling fluid and the substrate to a target level, particularly during the early stages of the cooling process when the substrate may be comparatively hot.

Control strategies 300 and 400 are over simplified in that they show the valves being incrementally opened or closed at every step whenever there is a difference between a measured value and its target. Control strategies are generally more complex, involving for example, proportional, integral and differential control. The strategy used depends on the dynamics of the system being controlled, but is selected to keep response times short and limit problems such as oscillation and overshoot.

While control strategies 300 and 400 both maintain an approximately constant overall cooling rate, it may be desirable to vary the cooling rate. During the early stages of the cooling process when the substrates are hotter, temperature variations in the substrates have greater effects. During the later stages of the cooling process, temperature differences may be less important and more rapid cooling may be permissible. Therefore, it may be desirable to increase the target temperature difference between the substrate and the fluid in the chamber as substrate temperature decreases.

In some situations the effect of temperature variations in the substrates may be mitigated by rapid overall cooling. For example, if the only effect of a temperature variation on a particular substrate is a difference in solvent evaporation rate, the effect will be mitigated if the entire substrate cools before significant evaporation takes place. In such circumstances, the control objective may be to maintain a low cooling

fluid temperature in the chamber. This may be accomplished by opening outlet valve 220 to a large extent so that the chamber pressure is nearly atmospheric and the flow rate of cooling fluid through the chamber is high.

The forgoing discussion of control strategies has been premised, to some extent, on the assumption that the overall heat transfer coefficient between the chamber gas and the substrates and the uniformity of heat transfer between the chamber gas and the substrates are not substantially affected by the pressure in the chamber or the flow rate of cooling fluid through the chamber. While these assumptions are valid in many circumstances, there are other circumstances where they become significant considerations. For example, when re-circulation within the chamber is low in comparison with the flow rate through the chamber, there may be significant variations in the cooling fluid temperature, which may result in non-uniform cooling of the substrates.

A control strategy aimed at maintaining an elevated pressure within the chamber may increase uniformity of cooling. Increasing the chamber pressure at constant mass flow rate through the chamber increases the residence time and thermal inertia of the fluid within the chamber. Higher thermal inertia and higher residence time will generally result in more uniform cooling. In one embodiment of the invention, the pressure in the chamber is maintained at or above about 2 bar. In another embodiment, the pressure in the chamber is maintained at or above about 10 bar. In a further embodiment, the pressure in the chamber is maintained at or above about 20 bar.

Fig. 4 illustrates a control strategy 500 for maintaining a high flow rate through the chamber and a constant pressure within the chamber. The target pressure may be, for example, the pressure necessary to maintain CO_2 in a supercritical state. In step 510, the chamber pressure is measured by meter 170. In step 520, controller 150 compares the measured chamber pressure to the target chamber pressure. If the measured chamber pressure is too high, controller 150 checks, in step 530, whether outlet valve 220 is fully open If it is fully open, inlet valve 140 is closed in step 550 by a proportionality factor, b, times the pressure difference. If outlet valve 220 is not fully open, outlet valve 220 is opened in step 540 by a proportionality factor, a, times the pressure difference. Proportionality factors a and b are proportional control

factors, which are selected by the user based on experience with the valves and the system dynamics.

If in step 520 the measure chamber pressure is less than or equal to the target pressure, control proceeds to step 560 wherein controller 150 checks whether inlet valve 140 is fully open. If it is fully open, outlet valve 220 is closed in step 540 by a proportionality factor, a, times the pressure difference. If outlet valve 220 is not fully open, inlet valve 140 is opened in step 550 by a proportionality factor, b, times the pressure difference. Steps 540 and 550 return control to step 510, so the process of measurement, comparison, and adjustment repeats. Differential and integral control can be added to strategy 500 (and strategies 300 and 400) if needed, to improve the control system's stability and responsiveness.

The methods of the invention may be used to limit the variation in temperature within and among substrates during cooling. In one embodiment, the temperature never varies by more then about 5 °C among and within the substrates 190. In another embodiment, the temperature never varies by more then about 2 °C among and within the substrates 190. In a further embodiment, the temperature never varies by more then about 0.5 °C among and within the substrates 190.

What has been described above is the present invention and several of its specific aspects. It is, of course, not possible to describe every conceivable combination of components or methodologies for purposes of describing the present invention, but one of ordinary skill in the art will recognize that many further combinations and permutations of the present invention are possible. Accordingly, the present invention is intended to embrace all such alterations, modifications and variations that fall within the spirit and scope of the appended claims.

What is claimed is:

1. A system for cooling coated semiconductor substrates, comprising:

a chamber adapted to receive one or more coated semiconductor substrates;

a coupling for placing the chamber in fluid communication with a fluid reservoir;

an inlet valve for controlling the flow of fluid between the fluid reservoir and the chamber; and

a controller that controls the inlet valve.

2. The system of claim 1 wherein the coupling is attached to a fluid reservoir and the pressure drop across the inlet valve is at least about 10 bar.

3. The system of clam 2 wherein the pressure drop across the inlet valve is at least about 100 bar.

4. The system of claim 1 wherein the controller controls the temperature of the fluid at a point within the chamber.

5. The system of claim 1 further comprising an outlet valve controlling the flow of fluid out of the chamber, wherein the controller also controls the outlet valve.

6. The system of claim 5 wherein the controller controls the rate of fluid flow through the chamber.

7. The system of claim 1 wherein the fluid entering the chamber from the reservoir substantially mixes with fluid already in the chamber before contacting the substrates.

8. The system of claim 7 wherein the fluid flowing into the chamber is

directed against a baffle.

9. A system for cooling coated semiconductor substrates comprising:

means for cooling a fluid by at least about 10 °C through the Joule-Thompson effect; and

means for contacting the substrates with the cooled fluid.

10. The system of claim 9 comprising means for cooling the fluid by at least about 25 °C through the Joule-Thompson effect

11. A method of cooling coated semiconductor substrates, comprising:

cooling a fluid by at least about 10 °C through the Joule-Thompson effect; and

contacting the substrates with the cooled fluid.

12. The method of claim 11 wherein the temperature of the cooling fluid is varied during the cooling process.

13. The method of claim 11 wherein the substrates are in a chamber and the temperature and/or flow rate of the cooling fluid entering the chamber are varied to maintain an approximately constant difference between the average fluid temperature in the chamber and the average substrate temperature.

14. The method of claim 11 wherein the pressure in the chamber is maintained at or above about 2 bar.

15. The method of claim 11 wherein the cooling fluid is heated before it is cooled.

16. The method of claim 11 wherein the temperature within and among the substrates never varies by more than about 2 °C over the course of the cooling process.

17. The method of claim 11 wherein the substrates are cooled within a chamber within which the substrates were previously heated.

18. The method of claim 11 wherein the flow rate of the cooling fluid is varied during the cooling process.

19. A method of cooling coated semiconductor substrates, comprising:

heating a fluid to a temperature above ambient;

subsequently flowing the fluid into a chamber containing the substrates; and

cooling the substrates by contacting them with the fluid.

20. The method of claim 19 wherein the temperature of the fluid entering the chamber is varied as the substrates cool.

21. A system for cooling coated semiconductor substrates, comprising:

a first sub-system for cooling a fluid using the Joule-Thompson effect; and

a second sub-system for contacting the coated semiconductor substrates with the cooled fluid.

Abstract of the Invention

According to the invention, resist coated wafers are rapidly and uniformly cooled by a fluid that has been cooled through the Joule-Thompson effect. Fluid from a high pressure reservoir is vented into a chamber that contains the substrates. By varying the pressure difference between the reservoir and the chamber, the temperature of the cooling fluid entering the chamber can be controlled. By also controlling the flow rate through the chamber, the average temperature difference between the fluid in the chamber and the substrates may be limited, whereby more uniform cooling is obtained. While the chamber pressure is lower than that in the high pressure reservoir, the chamber pressure may still be substantially greater than atmospheric. An elevated chamber pressure raises the specific heat and residence time of the fluid in the chamber, which also promotes uniform cooling.

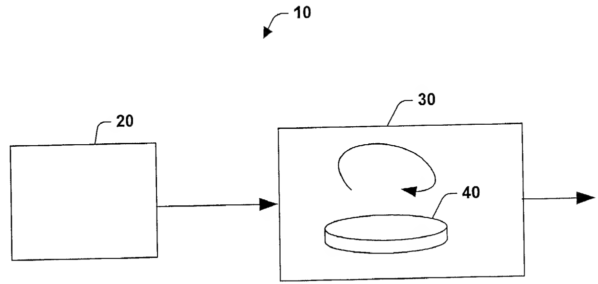


FIG. 1a

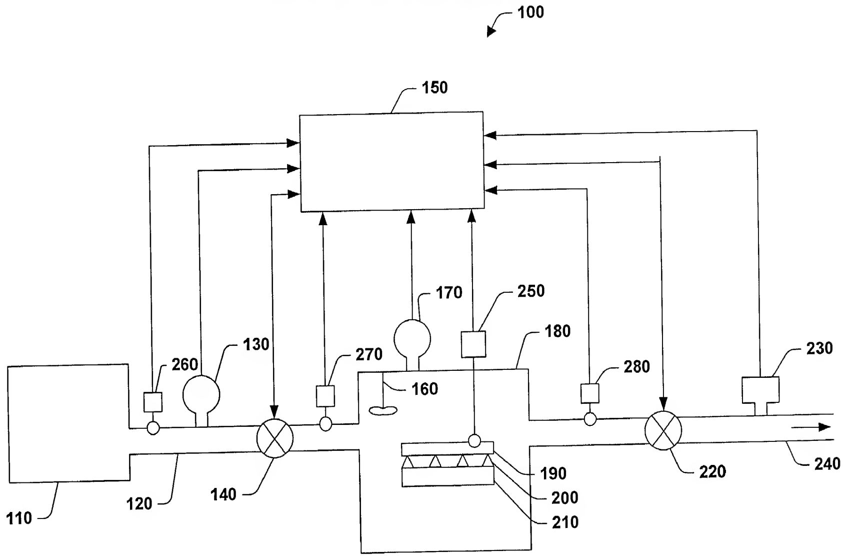
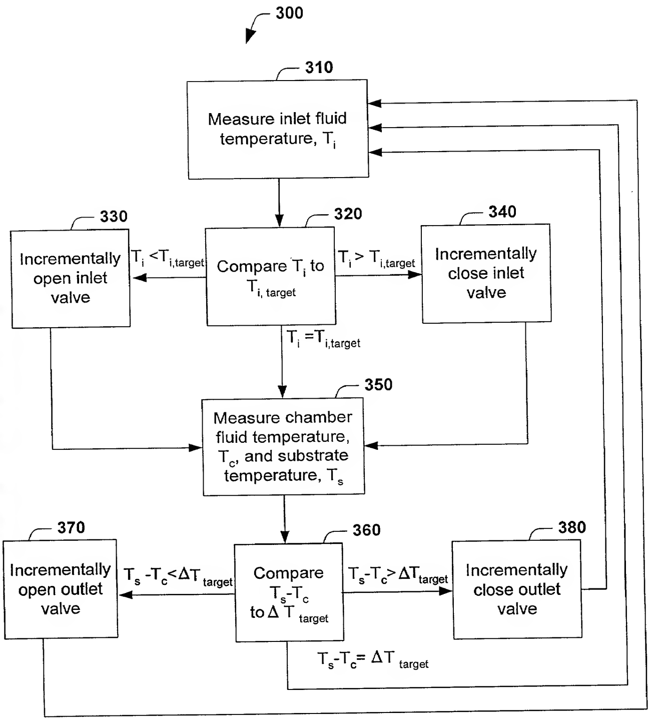

100
150
170
250
180
130
260
270
280
230
160
190
200
210
220
240
110
120
140

FIG. 1b



300
310
Measure inlet fluid temperature, T_i
320
Compare T_i to $T_{i, target}$
330
Incrementally open inlet valve
340
Incrementally close inlet valve
$T_i < T_{i,target}$
$T_i > T_{i,target}$
$T_i = T_{i,target}$
350
Measure chamber fluid temperature, T_c, and substrate temperature, T_s
360
Compare T_s-T_c to ΔT_{target}
370
Incrementally open outlet valve
380
Incrementally close outlet valve
$T_s - T_c < \Delta T_{target}$
$T_s - T_c > \Delta T_{target}$
$T_s - T_c = \Delta T_{target}$

Fig. 2

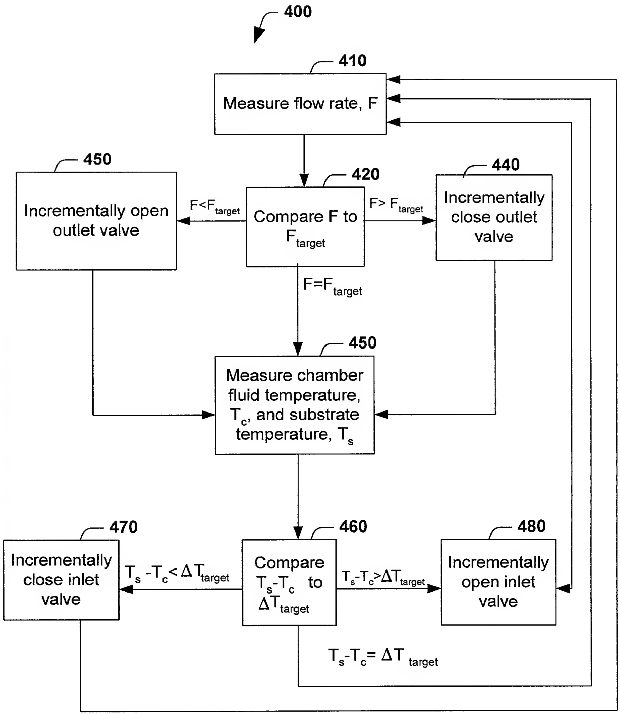

400
410
Measure flow rate, F
420
Compare F to F_{target}
$F<F_{target}$
$F>F_{target}$
450
Incrementally open outlet valve
440
Incrementally close outlet valve
$F=F_{target}$
450
Measure chamber fluid temperature, T_c, and substrate temperature, T_s
460
Compare T_s-T_c to ΔT_{target}
$T_s - T_c < \Delta T_{target}$
$T_s - T_c > \Delta T_{target}$
470
Incrementally close inlet valve
480
Incrementally open inlet valve
$T_s - T_c = \Delta T_{target}$

Fig. 3

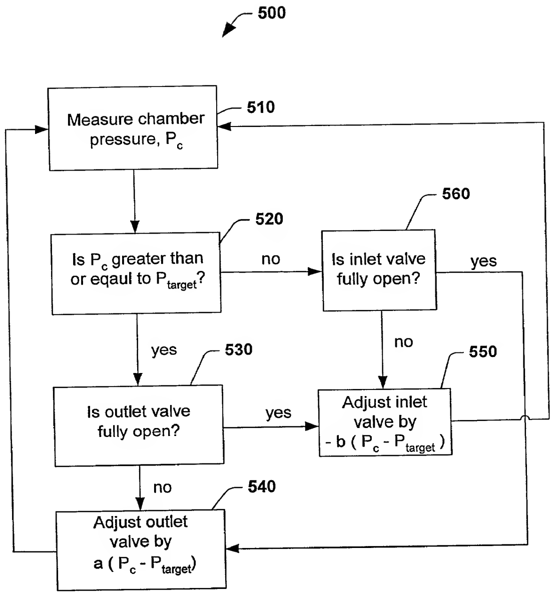

500
Measure chamber pressure, P_c
510
Is P_c greater than or eqaul to P_{target}?
520
no
Is inlet valve fully open?
560
yes
yes
530
Is outlet valve fully open?
yes
no
Adjust inlet valve by $-b(P_c - P_{target})$
550
no
Adjust outlet valve by $a(P_c - P_{target})$
540

FIG. 4

COMBINED DECLARATION AND POWER OF ATTORNEY
(ORIGINAL, DESIGN, NATIONAL STAGE OF PCT)

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name, I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled: **SYSTEM FOR RAPIDLY AND UNIFORMLY COOLING RESIST**

the specification of which

(a) _X_ is attached hereto.
(b) ___ was filed on ____________________ as ___ Serial No. 0 /___________ or Express Mail No.________________, as Serial No. not yet known, and was amended on _________ (if applicable).
(c) ___ was described and claimed in PCT International Application No. ______________________ filed on _____________________ and amended under PCT Article 19 on ___________ (if any).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability in accordance with Title 37, Code of Federal Regulations §1.56(a).

PRIORITY CLAIM

I hereby claim foreign priority benefits under Title 35, United States Code, §119 of any foreign application(s) for patent or inventor's certificate or of any PCT international application(s) designating at least one country other than the United States of America listed below and have also identified below any foreign application(s) for patent or inventor's certificate or any PCT international application(s) designating at least one country other than the United States of America filed by me on the same subject matter having a filing date before that of the application(s) of which priority is claimed.

(d) _X_ no such applications have been filed.
(e) ___ such applications have been filed as follows.

EARLIEST FOREIGN APPLICATION(S), IF ANY FILED WITHIN 12 MONTHS (6 MONTHS FOR DESIGN) PRIOR TO THIS U.S. APPLICATION

COUNTRY	APPLICATION NUMBER	DATE OF FILING (day, month, year)	PRIORITY CLAIMED UNDER 35, USC 119
			___ Yes ___ No
			___ Yes ___ No
			___ Yes ___ No

ALL FOREIGN APPLICATION(S), IF ANY FILED MORE THAN 12 MONTHS (6 MONTHS FOR DESIGN) PRIOR TO THIS U.S. APPLICATION

AMD Docket No. E0794

PATENT

POWER OF ATTORNEY

As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith. (List name and registration number)

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The undersigned to this declaration and power of attorney hereby authorizes the U.S. attorney(s) named herein to accept and follow instructions from

Name(s) of authorized representative(s)__________

Address__________

as to any actions to be taken in the Patent and Trademark Office regarding this application without direct communication between the U.S. attorney(s) and the undersigned. In the event of a change in the person(s) from whom instructions may be taken, the U.S. attorney(s) will be so notified by the undersigned.

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with knowledge that willful false statements and the like are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued therein.

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X This declaration ends with this page.